TRACER STUDIES OF MIXING IN STRATIFIED COASTAL WATERS

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LONG TERM GOALS

Long term goals of the project are:

1. To enable prediction of vertical and lateral mixing from stratification, current and shear characteristics within continental-shelf waters.
2. To provide mixing estimates for use in models of optical properties of continental shelf waters.

SCIENTIFIC OBJECTIVES

There are four major objectives. These are: (1) To measure vertical mixing and lateral mixing and stirring with 3- to 5-day dye release experiments in two seasons on the continental shelf, in the pycnocline and in the bottom boundary layer. (2) To compare the vertical mixing coefficients with estimates from measurements of the dissipation rates of turbulent kinetic energy and temperature variance at both levels in the water column, and with measurements of Reynolds stress and heat flux in the bottom boundary layer. (3) To determine the dominant mechanisms of both vertical and lateral mixing on the continental shelf. (4) To develop parameterizations of both vertical and lateral mixing in terms of more easily measured hydrography and current shear.

APPROACH

The scientific approach is the release of dye patches as close as possible to target density surfaces and to measure the subsequent dye dispersion over periods of 3 to 5 days. Sampling for the dye is performed with a tow-yo'd CTD/Optics package. The dispersion of the dye can be directly compared with turbulence measurements made with the loosely tethered EPSONDE profiler by N. Oakey during the dye experiments, and with our own towed microstructure measurements. Dr. Oakey is funded under a separate grant within the Coastal Mixing and Optics Program, entitled "Turbulent microstructure studies in coastal ocean boundary layers". He deployed the EPSONDE and ELITESONDE profilers during the dye survey cruises, measuring dissipation rates of turbulent kinetic energy and temperature variance within the dye patches

WORK COMPLETED

Three cruises on R/V Oceanus have been completed: a 5-day pilot cruise in September 1995 with a single dye release, a 15-day cruise in September 1996 with two dye releases, and a 15-day cruise in August 1997 with two dye releases, for a total of five experiments.

All of the experiments took place between the 60 and 80 m isobaths within 40 km of the central mooring for the Coastal Mixing and Optics experiment, which was at 40.5 N, 70.5 W, half-way across the continental shelf, and 90 km south of Martha's Vineyard. Each dye release was followed with two or three surveys over a period of between 60 and 120 hours. Most of the surveys delimited the patch well laterally and vertically, allowing quantitative measures of lateral and vertical dispersion between surveys. The initial dye streaks were between 1 and 2 km long and were confined to within 1 to 2 m rms of a target isopycnal surface. After four days the dye patches had spread laterally over an area on the order of 100 km^2, while drifting as much as 40 km along isobaths. The spread of the dye across density surfaces (diapycnal spread) was small, never growing to more than 4 m rms in four days.

The depths of the releases varied from 16 to 62 m, so that the water column was probed from the upper pycnocline to the bottom boundary layer (Table 1.). The buoyancy frequency *N*, which is a measure of the strength of the stratification, varied at the levels of release from 6 cph to 18 cph. Preliminary estimates of the diapycnal diffusivity in each case have been made.

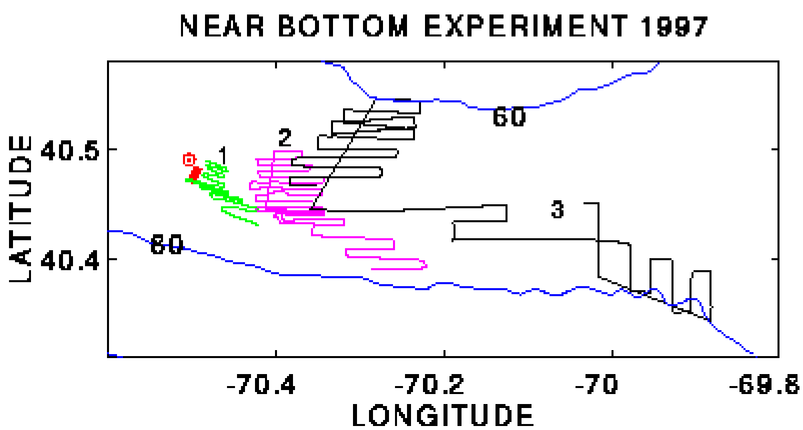

Fig 1. Survey tracks.

Let us illustrate the dye experiments with the second experiment in 1997, in which the dye was released 5 to 10 m off the bottom. Figure 1 shows the initial streak in red just southeast of the bottom boundary layer tripod of Trowbridge and Williams, also shown in red. The tracks labeled 1, 2, and 3 are dye surveys performed within one day of release, 2 to 3 days after release, and 4 to 5 days after release, respectively. The column integral of dye for the last survey is mapped in Fig. 2, in a coordinate system moving with the dye patch as estimated from the ADCP record. The dye was strongly sheared offshore toward the east. Figure 3 shows the distribution of dye concentration (color and dashed contours) and potential density (solid contours) as a function of offshore distance. The onshore part of the patch is concentrated near the bottom, and was most likely brought onshore by an Ekman flow, while it mixed to relatively low densities. The offshore part of the patch is separated from the bottom, except for a foot of the distribution at the 68 meter

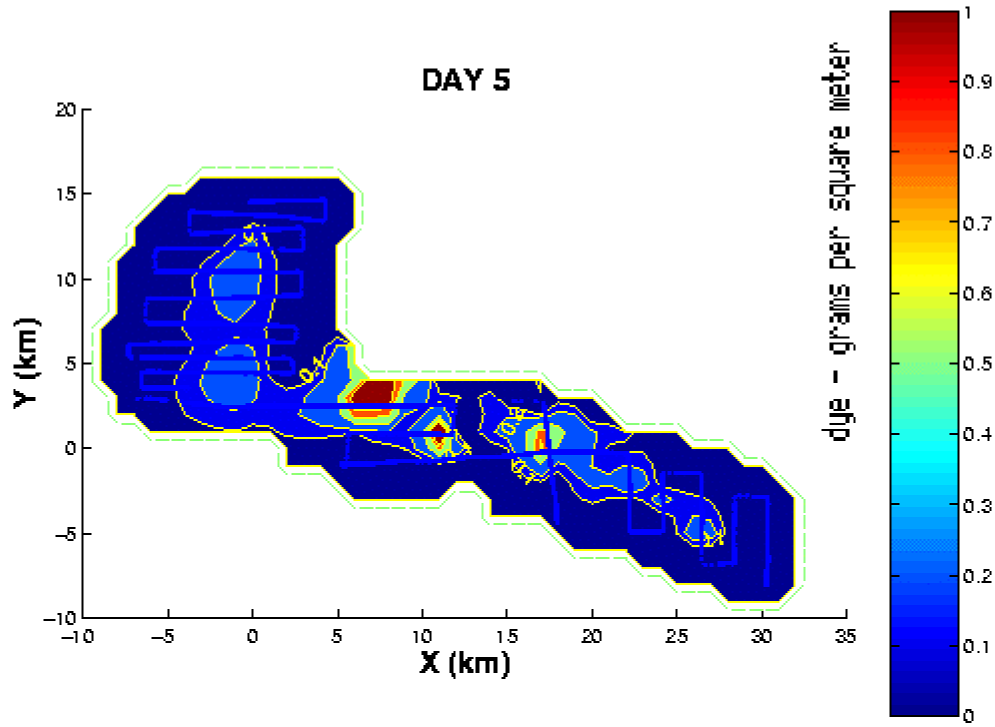

Fig. 2

isobath, which has mixed to relatively large density. The spread of the dye across density surfaces since the release indicates diffusivities of under 0.1 cm^2/s, except possibly within 2 or 3 meters of the bottom.

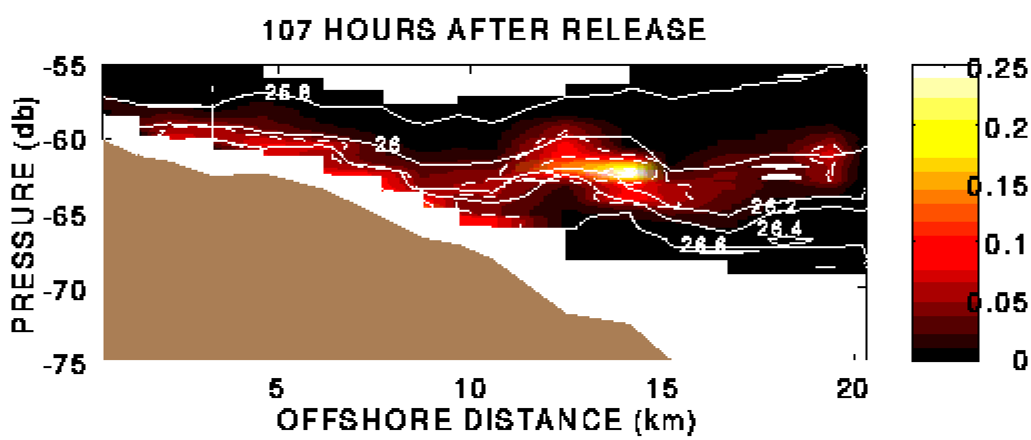

Fig. 3.

Hundreds of profiles of turbulent dissipation rates with the ESPSONDE profiler by N. Oakey were performed between the dye surveys in 1996 and 1997, under a separate grant. Inferences of diapycnal diffusivity from these data will be compared with the results of the dye experiments.

Measurements of conductivity microstructure from the same towed body used for dye sampling were made in 1997, under this grant. Preliminary estimates of diapycnal diffusivity have been made from these data for comparison with diffusivities inferred from the dye experiments.

Velocity and shear measurements were made during the experiments to help track the tracer patches and to characterize the motions associated with lateral spreading and the shear feeding energy to small scales for diapycnal mixing. An existing narrow-band Acoustic Doppler Current Profiler (ADCP) was used during the 1995 pilot study, while in 1996 and 1997 a broadband unit purchased under a DURIP contract related to this project was used. The vertical resolution of the broadband ADCP was 2 meters. A very effective program was developed to process the ADCP data and to integrate the velocity at the level of the dye patch quickly enough to adjust the sampling track for drift of the patch during surveys.

Up to six holey-sock drogues were released with the dye patches in each experiment to help track the dye and to add information on lateral dispersion. These drogues were tracked by ARGOS satellite and were recovered each time, with relatively small losses.

RESULTS

Preliminary estimates of the diapycnal diffusivities from each of the dye experiments are listed in Table 1. These will be refined further over the coming months. However, it is already clear that the diapycnal diffusivity is between 0.01 and 0.1 cm^2/s in most cases studied. The only exception is the experiment at 33 meters depth at relatively weak stratification, N = 6 cph, when the diffusivity was on the order of 0.3 cm^2/s, still quite small. Wind speeds during all of the experiments were generally less than 10 m/s, so the wind forcing was small. The experiments were done during various phases of the spring-neap cycle of the tides. The conclusion is that diapycnal mixing is small during normal summertime conditions, in the sense that the distribution of temperature, salinity, and passive tracers will not be much affected by diapycnal diffusion in the time it takes for water to flow hundreds of km along the shelf. This is consistent with our towed microstructure records, which contain lengthy periods of no turbulent signature. Exceptions occur during severe storms. For example, the water column had obviously been strongly mixed by the passage of Hurricane Edouard, just prior to the cruise in September 1996.

Preliminary comparison of the diapycnal diffusivity inferred from the dye experiments with that inferred from the profiles of dissipation rates by Oakey indicate that the two are within a factor of 2 or 3 of one another. Careful averaging in the appropriate density window must yet be done for both techniques to obtain the final comparison.

Studies of lateral dispersion so far have suggested that the interaction of vertical shear with vertical mixing is not strong enough to explain the observed spreading of the dye patch. This may be the most exciting finding of the experiment, pointing to a mechanism that is not yet identified. Graduate student Miles Sundermeyer is exploring this problem.

IMPACTS/APPLICATIONS

The demonstration that diapycnal mixing is slow on the shelf in summertime conditions will constrain dynamical theories and numerical models in a way that will tend to make them clearer and simpler. Knowledge that the diapycnal diffusivities are low will also constrain the interpretation of field observations of biogeochemical distributions, and models of biogeochemical processes, including those involved in determining the optical characteristics of the water column over the shelf.

The comparison of the dye dispersion with the diapycnal diffusivity inferred from the dissipation rates is the first to be done in the ocean at temporal and spatial scales that are well matched for the two techniques. The implications for the interpretation of dissipation measurements, and hence for estimates of diapycnal mixing in scores of applications are great.

Table 1. Summary of Diapycnal Mixing Studies

Experiment	Depth (m)	N (cph)	K (cm^2/s)
September 1995	40	13	< 0.15
September 1996	33	6	~ 0.4
September 1996	47	10	0.02 to 0.1
August 1997	16	16	~0.02
August 1997	62	18	0.02 to 0.1

RELATED PROJECTS

The cruise was an integral part of a series of cruises in summer and fall 1996 within the Coastal Mixing and Optics Program (CMO). We have made some of our data available already to the CMO community, particularly those data related to the effects of Hurricane Edouard. The results on diapycnal diffusivity will be an integral part of the interpretation of the hydrographic, kinematic and optical data that will be gathered by other participants in CMO, and ultimately to all those interested in oceanographic processes on the continental shelf.

PUBLICATIONS AND PRESENTATIONS:

CMO Dye and Microstructure web pages containing additional information are accessible from **`http://cofdl.whoi.edu/cmotop.html`**, along with three cruise reports.

Four presentations of this work are planned for the Feb. 1998 AGU Ocean Sciences meeting. One focuses on the vertical dye dispersion, one on the towed microstructure findings, one on the front and jet features in the area, and one on the lateral dye dispersion.